Verification of the Implementation of RUC and ARPS Cloud Analysis Procedures in GSI with 13 March 2006 Central US Squall Line Case

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1. Introduction

The RUC and ARPS cloud analysis packages have been adapted into the GSI separately. This technique report documents the results of the RUC and ARPS cloud analysis and testifies the proper functions of the both packages in the GSI. The 13 March 2000 central US squall case was employ as testing case.

2. March 13, 2006 central US squall case

From 15 UTC March 12 to 09 UTC March 13, 2006, a strong surface low propagated through central US with its center starting from southeast Colorado, through Kansas, and ending at northeast Missouri. Associated with the strong low was a strong cold front moving east-southeastwards through Southern Plains and a strong warm front moving northwards. A dryline also existed before the cold front and moved eastwards during this period. Strong synoptic forces encountering convective-favorable environments produced a series of violent squall lines in central US. 140 tornadoes were reported during this severe weather event which caused 10 fatalities and huge property damages. As an example of environment field, the surface analysis map at 03 UTC 13 March 2006 is shown in Fig. 1.

Among several squall lines occurred during the day, the one used to test our scheme here was initiated along northeast Oklahoma, east Kansas, and northwest Missouri at around 2330 UTC 12 March and entered its mature stage from 01 UTC 13 March. This squall line lasted only 5 hours and replaced by a stronger squall line formed right behind it. The satellite IR image at 0315 UTC 13 March and base-level radar reflectivity at 0303 UTC 13 March are shown in Fig. 2 and Fig. 3, respectively. A squall line across Missouri to east Iowa was clearly observed by both Satellite and Radar. Also, both observations indicate a new squall line was initiating right follow the mature one at east Kansas.

3. RUC and ARPS cloud analysis in GSI and experimental design

The RUC and ARPS cloud analysis have been adapted into the GSI through the GSI framework, which is a copy of the GSI but skip variational analysis step. The RUC cloud analysis can use Metar and NESDIS cloud products to generate stratus cloud coverage and cloud ice and cloud water mixing ratio inside the cloud domain, while the ARPS cloud analysis uses Metar and NSSL mosaic reflectivity to decide cloud and precipitation coverage and generate cloud water, cloud ice, rain, snow, and hail. Also in the ARPS cloud analysis, in-cloud temperature is adjusted to offset the negative buoyancy and support the further development of storms. Currently, the two cloud analysis packages can only be used separately.

Table 1 List of testing experiments with cloud analysis package and data used

name	Cloud analysis	Background	Cloud observation type used
RUC_both	RUC	NAM+ARPS	Metar + NESDIS
RUC_NESDIS	RUC	NAM+ARPS	NESDIS
RUC_METAR	RUC	NAM+ARPS	Metar
ARPS_both	ARPS	NAM+ARPS	Metar + Mosaic reflectivity
ARPS_METAR	ARPS	NAM+ARPS	Metar
ARPS_RADAR	ARPS	NAM+ARPS	Mosaic reflectivity
RUC3	RUC	RUC2Z+1h	Metar + NESDIS+Mosaic reflectivity
RUC3_RUCbk	RUC	RUC2Z+1h	Metar + NESDIS+Mosaic reflectivity
ARPS2_RUCbk	ARPS	RUC2Z+1h	Metar + Mosaic reflectivity

There are totally six experiments conducted to test the functions of cloud analysis in the GSI framework and the only differences among them are which cloud analysis package is used and the type of observations employed by the analysis. Table 1 lists the cloud analysis package and data used by each experiment. RUC3 is a new experiment that uses NSSL mosaic reflectivity in the RUC cloud analysis to generate rain and snow fields. To study the effects of background field in the RUC cloud analysis, 2 additional experiments, RUC3_RUCbk and ARPS2_RUCbk, were conducted, in which the 1 hour forecast of RUC starting from 02 UTC were used as analysis background and RUC3 and ARPS_both were repeated with the new background and at new 13 km RUC grid.

All experiments were conducted at a grid with 9-km horizontal grid spacing and 30 uneven-distributed vertical sigma levels. To shown the functions of cloud analysis, the analysis was conducted at 03 UTC 13 March 2006, at which the quall line had fully developed and been observed by observation tools used here. First, the original GSI analysis was conducted in which background was interpolated from NAM three hour forecast valid at 03 UTC and only conventional observations in PREPBUF file were used. Then cloud analysis in the GSI framework was conducted with the background from the results of the GSI analysis to generate the initial fields that include cloud and precipitation information such as cloud water and cloud ice and rain, snow, hail. Finally, one hour forecast using the WRF-ARW model from these initial fields were completed. In this report, only analysis results are investigated to testify the cloud analysis packages in the GSI.

4. Results of RUC cloud analysis in GSI

In the RUC cloud analysis, the NESDIS cloud products, which include cloud top temperature and height, and cloud fraction, are used to determine the cloud distribution. To check the effects of those products, the analyzed cloud top heights are plotted in Fig. 4 for the experiments in which the NESDIS cloud products data are used. Comparing Fig. 4b to Fig. 2, which shows the satellite observed cloud top temperature, the analyzed cloud top distribution matches the observed one in terms of the locations and shapes of the cloud top along the quall line and four high cloud systems west of the squall line. Also, we note that the cloud top temperature observed by Fig. 2 can only be used locally to identify relatively height of cloud top in one cloud system. When compare cloud systems at different latitudes, in this case the one located at the west coast of the Gulf of Mexican and the one at northeastern Minnesota, it is found that the former has higher top than the later in the analyzed cloud field but the former has lower cloud top temperature than the later in the IR observation. Obviously, this reflects the different characteristics of high latitude cloud system and low latitude cloud system. When Metar data were added in the analysis, lots of low cloud systems are induced into the results (Fig. 4a).

To check the cloud liquid water content (LWC) and precipitation added by the analysis, the composite reflectivity and the vertical amount of total water mixing ratio from the three RUC cloud analysis experiments are plotted in Fig. 5. Because the RUC cloud analysis package in GSI dose not analyze any precipitation species, reflectivity is 0 in all three experiments (Fig. 5a, c, and e). In this case, the vertical amount of total water mixing ratio reflects the horizontal coverage of cloud system and the total value of LWC in a vertical column. When only NESDIS data were used in the experiment RUC_NESDIS, the analyzed cloud coverage captures the cloud domain observed by the satellite (Fig. 2 and Fig. 5d) but the total value of LWC is small with the maximum value of 0.365 g/kg, which indicates the RUC cloud analysis mainly aims to analyze stratiform clouds (RUC has a cap of 0.1 g/kg for the LWC in a grid). When only Metar data were used, the analyzed cloud coverage shows two cloud bands, big one covering the northern US from Wyoming to the northeast coast of US and small one covering the coast of the Gulf of Mexico (Fig. 5f). Both cloud bands have been observed by satellite (Fig. 2) but the analysis misses the cloud system of the squall line that caused huge damage in the central US. The analysis of cloud coverage and LWC using both Metar and NESDIS data is the combination of the analysis when the two datasets are used separately (Fig. 5d, e, f). We note that the maximum LWC of the experiment RUC_METAR is much bigger than others. This big value comes from the conversion of visibility to LWC when observed visibility is 0. The problem has been temporarily solved by setting a cap (10m or 100m) for minimum visibility.

The vertical distributions of analyzed cloud are plotted in Fig. 6, which is the X-Z cross-sections of cloud ice and cloud water from the experiments using RUC scheme. When only Metar data were used, the cloud mainly distributes in low atmosphere (Fig. 6c and d), while the experiments using the NESDIS data only determine the cloud distribution from the location of cloud top and the analyzed cloud distributes mainly in middle and upper atmosphere (Fig. 6e and f). When both were used, the cloud can be distributed in the entirely atmosphere but usually with some gaps between analyzed low and high clouds (Fig. 6a and b). The values of cloud ice and cloud water added in the cloud domain are also different among these two datasets. Usually, low cloud has much more liquid content than high cloud and therefore Metar data can add more LWC that satellite data do. Because of the high horizontal-vertical ratio (3200 km versus 13 km) in the figure, the clouds seem like convective and extend mainly in the vertical. But when we check the clouds in the figures that have similar vertical-horizontal ratios (figures no shown), the clouds distribute mainly horizontally, which are consistent with that the RUC cloud analysis focuses on the analysis of stratiform clouds.

5. Results of ARPS cloud analysis in GSI

The ARPS cloud analysis can use Metar and radar reflectivity to generate cloud and precipitation distribution and hydrometers in cloud and precipitation system. Similar to the above analysis of the RUC package, the composite reflectivity and the vertical amount of total water mixing ratio from three ARPS cloud analysis experiments are plotted in Fig. 7.

When only Metar data were used, the analysis gives two similar but wider cloud bands as the RUC cloud analysis did (Fig. 7f and Fig. 5f). In the ARPS cloud analysis, the precipitation species also can not be decided by Metar data and the analyzed reflectivity of ARPS_METAR is 0 (Fig. 7e). By using radar reflectivity data, the domain and strength of the precipitation systems are accurately generated through the ARPS cloud analysis procedure (Fig. 7c, Fig. 3), but the cloud coverage is also limited within the reflectivity region or precipitation region (Fig. 7c and d). The experiment with both Metar and radar reflectivity combines the effects of the two datasets (Fig. 7). Comparing the values of the content of the analyzed hydrometers in the ARPS cloud analysis to the RUC cloud analysis, the former is much higher than the later because the ARPS cloud analysis mainly considers the strong convective clouds which have much higher liqiud water contents.

The X-Z cross-section of cloud ice, cloud water, snow, rain, and hail from the experiments ARPS_Metar, ARPS_RADAR, and ARPS_both are plotted in Fig. 8, Fig. 9, and Fig. 10, respectively, with an additional cross-section of analyzed reflectivity field from the experiment ARPS_both plotted in Fig. 10f. Again, we can see that the Metar data mainly provide the cloud information in low atmosphere and the analyzed cloud ice and cloud water are located at the levels below 5 km (Fig. 8). When radar data were used, the vertical extension of precipitation is fully explored and the cloud and precipitation system can cover the whole column (Fig. 9). Specifically in this case, the cloud ice distributes in the levels from 5 to 9 km; the cloud water are in the levels below 6 km; snow shows in the levels above 3 km and can research as high as 12 km; rain distributes in the levels below 3 km; hail are between 2 km and 9 km. Both rain and hail are in high-extended strong reflectivity area. Because of the fully vertical extension of radar data, the analysis results of ARPS_both are dominated by the radar reflectivity in the region where both Metar and reflectivity data are available (Fig. 8, Fig. 9, and Fig. 10).

One of important function of the ARPS cloud analysis is in-cloud temperature adjustment according to either moist adiabtic or LWC added in the analysis. In this case, the scheme using the moist adiabatic is tested and the maximum temperature increasing is about 5 degree.

6. Detailed vertical distributions of hydrometers

To see the vertical distributions of hydrometers in the cloud analysis, a small portion of X-Z cross-section of hydrometer fields from the experiment RUC_both and ARPS_both is plotted in Fig. 12 and Fig. 11, respectively. The main difference between the two cloud analysis schemes is the thickness of clouds. The RUC assumes all clouds are stratiform and therefore adds a thin layer of clouds from cloud top, which is decided by NESDIS cloud products, or from the cloud base, which is decided by the METAR observations (Fig. 12). The ARPS can decide the cloud and precipitation types of each grid, but generally add a thicker layer of cloud than the RUC does based on cloud base from METAR data. When radar reflectivity data are used, the thickness of the cloud is decided by the vertical range of the reflectivity observations. From Fig. 11, we can see the hydrometers distribute within the reflectivity area with clouds covering low reflectivity area and precipitations covering high reflectivity area. We also see the cloud water and cloud ice of the experiment ARPS_both have much higher value than that of the experiment RUC_both due to the different vertical curves used to consider entrainment of clouds.

7. Analysis Results from Experiment RUC3

RUC3 is a new experiment that uses NSSL mosaic reflectivity in the RUC cloud analysis to generate rain and snow fields. From this experiment, we can see:

- The NSSL mosaic reflectivity data have been successfully read into and used by RUC cloud analysis (Fig. 13).
- The values of rain and snow from reflectivity are too large (Fig. 13b, Fig. 14c,d). We need to look into the equations used for retrieving rain and snow from reflectivity.
- The rain and snow cover the high reflectivity area (Fig. 14c, d).
- The clouds from Metar data are all below 2 km and show as thin layer.

8. Analysis with background from RUC 1-h forecast

To study the effects of background field in the RUC cloud analysis, RUC3_RUCbk and ARPS2_RUCbk, were conducted, in which the 1 hour forecast of RUC starting from 02Z 13 March 2006 were used as analysis background and RUC3 and ARPS_both were repeated with the new background and at new 13 km RUC grid. Here are some thoughts from the results of RUC3_RUCbk after first look (Fig. 15, Fig. 16).

- RUC capture the cloud and precipitation system related with synoptic low and front but miss the squall line.
- RUC3_RUCbk adds the squall line according to reflectivity and also clean some hydrometers in the background according to Metar and satellite observations.
- Analyzed cloud water and cloud ice fields are dominated by background values while analyzed rain and snow fields are dominated by results of the RUC cloud analysis with radar reflectivity.
- The rain and snow from RUC cloud analysis are too large, need to change reflectivity equations.

The points made from the results of ARPS2_RUCbk are listed here (Fig. 15,Fig. 17):

- The ARPS cloud analysis can work well with RUC background and not only add precipitation species into initial fields, but also, it clear the spurious precipitation specious within the observation domain. (Fig. 15e, f). The analyzed reflectivity and volume amount of total water mixing ratio of ARPS2_RUCbk is much lower than those of RUC3_RUCbk
- In the current ARPS cloud analysis, the background values are not used in the area that has cloud observations. So, there is not background information in most of the analyzed domain. Only background information can be found near the surface where below the radar observation domain. (Fig. 17f)
- Cloud water and cloud ice of ARPS2_RUCbk have the similar distribution as that of ARPS_both but have a little smaller values, which maybe come from the interpolation from 13km RUC grid to 9km plot grid. (Fig. 17a, b)
- The values and distributions of rain, snow, hail in ARPS2_RUCbk are much different from those of ARPS_both because they were analyzed based on different background field. Snow is much larger in ARPS2_RUCbk but rain and hail are much smaller. (Fig. 17c, d, e)
- The rain and snow of ARPS2_RUCbk are much smaller than that of RUC3_RUCbk. (Fig. 17c d and Fig. 16h, i)

9. Results of 1-h forecast

Note: GSI is experiment that forecast starts from original GSI analysis without any cloud analysis.

The composite reflectivity and the vertical amount of total water mixing ratio from 1-h forecast of the experiments GSI, ARPS_both, RUC_both, and RUC3 are plotted in Fig. 18, while the radar reflectivity at the same time is plotted in Fig. 19. These forecasts show that

- GSI-ARW system can capture the synoptic precipitation and cloud system that located in north of the surface low and before of the warn front (Fig. 18a and b) but miss the squall line cross central Missouri and northwest Illinois.
- RUC cloud analysis does not affect the forecast because only stratiform cloud are added, which are the results of synoptic force and have been well predicted by current model.
- Both RUC3 and ARPS_both capture the quall line missed by the experiment GSI. The results indicate the important impacts of the radar reflectivity.
- RUC3 over-adds rain and snow. Need to repeat experiment to check the forecast after using proper reflectivity equations.
- The effects of in-cloud temperature adjustment are not shown in the experiment. Need special experiment to study this issue.

10. Conclusion

Through the analysis of these 6 experiments, we can conclude that the RUC and ARPS cloud analysis package have been successfully adapted into the GSI system and the observations needed by the analysis are also processed correctly. The main components of the both packages work properly. In the analysis, we can see both systems have their own main target of clouds and successfully capture the main features of the target clouds. Now we should combine them together to fully describe the full spectrum of the cloud system.

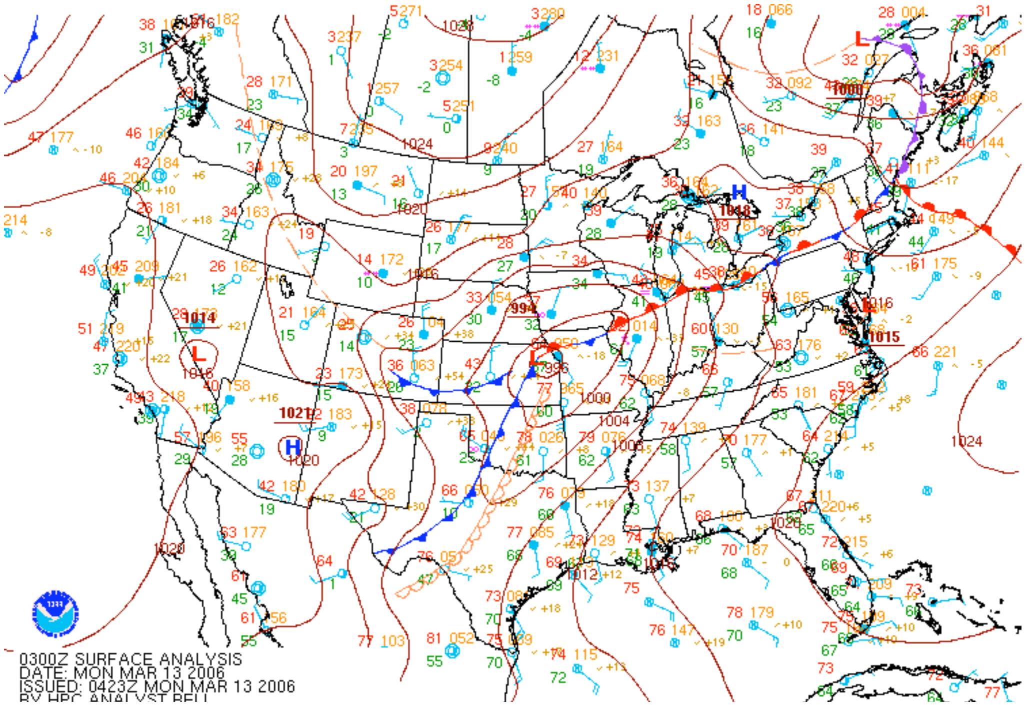

Fig. 1 Surface analysis at 03 UTC 13 March 2006 from HPC

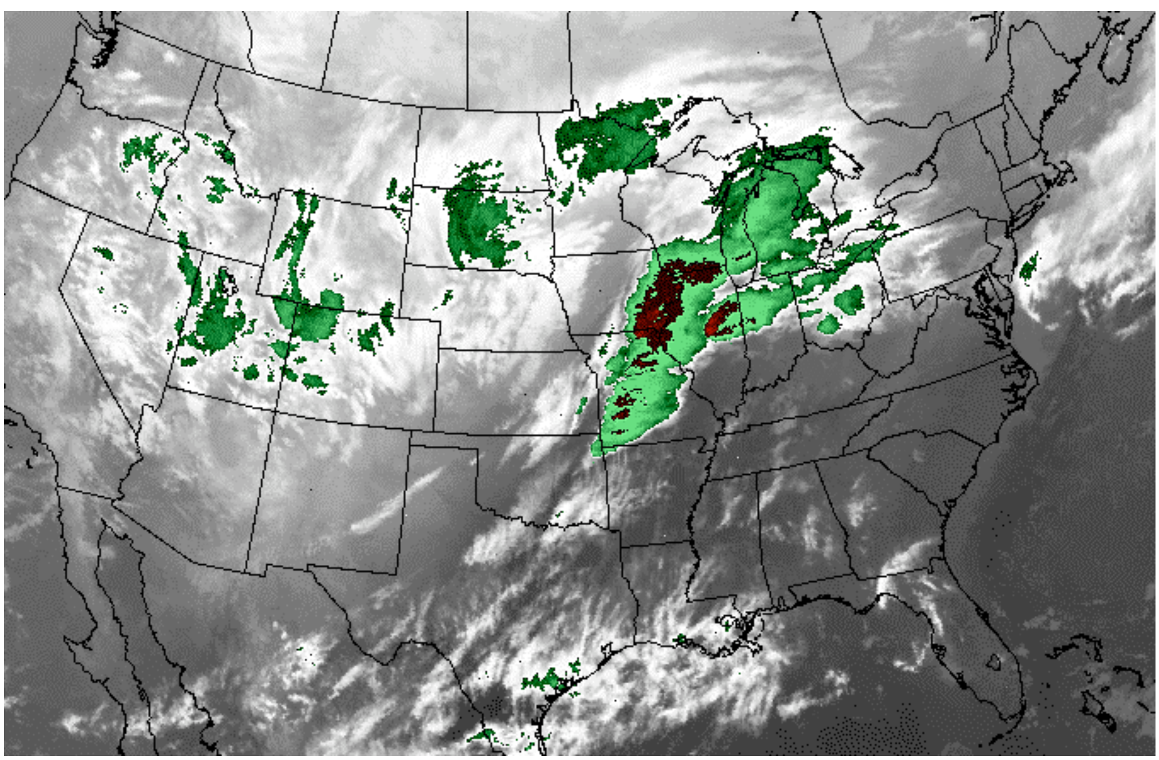

Fig. 2 IR image at 0315 UTC 13 March 2006

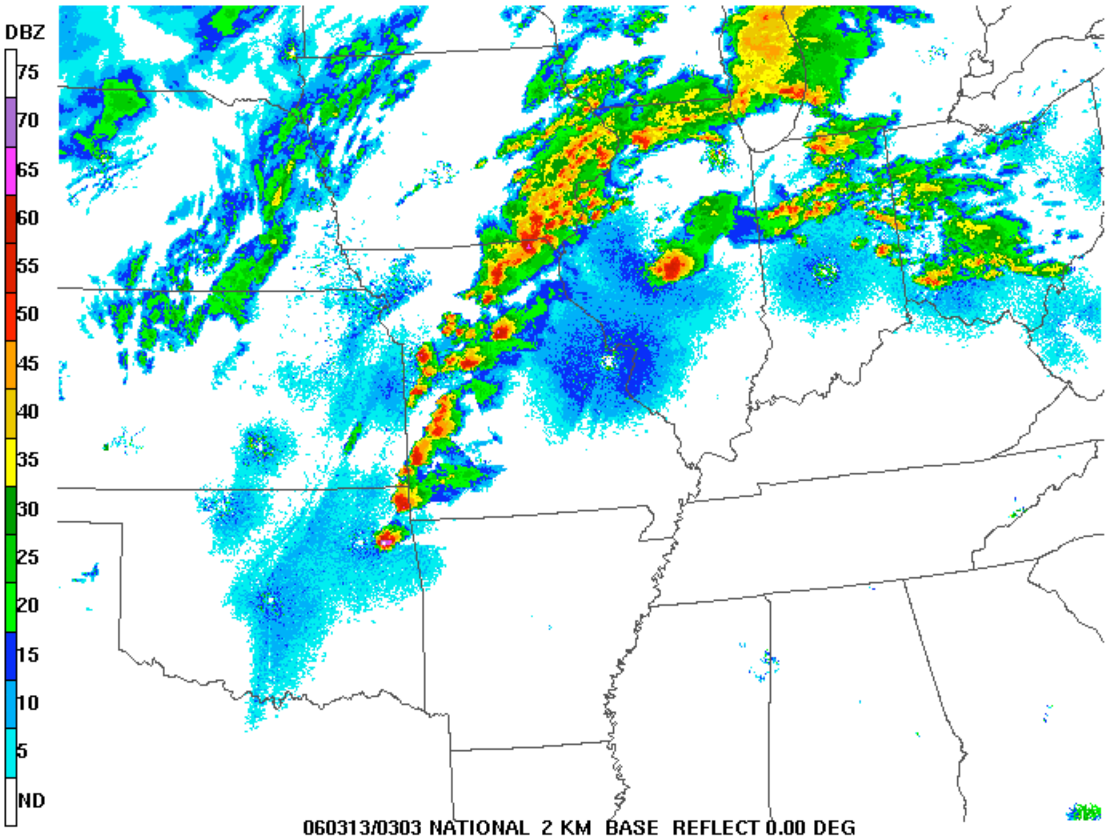

Fig. 3 Radar base reflectivity at 0303 UTC 13 March 2006

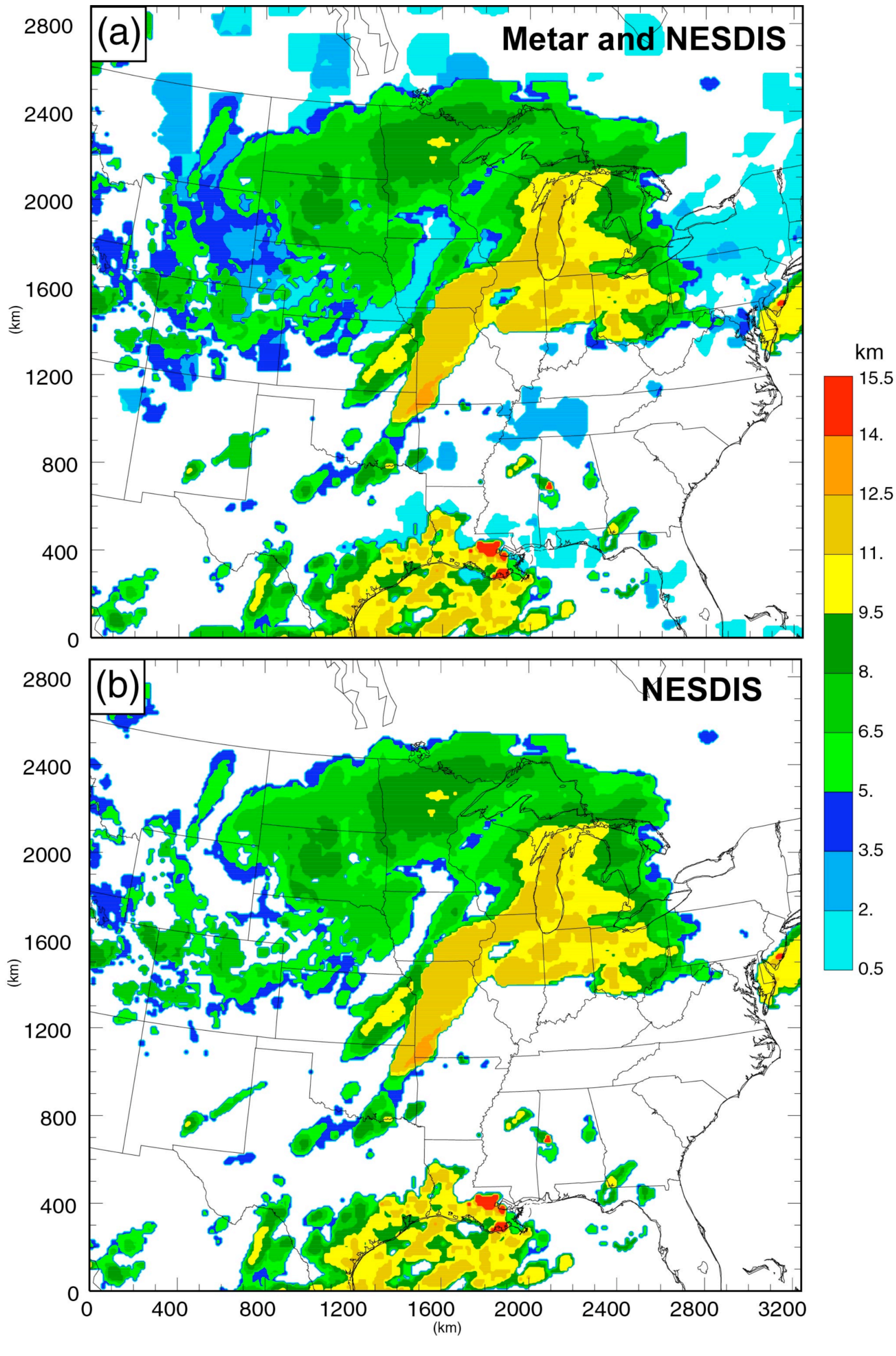

Fig. 4 The height of cloud top from the experiment RUC_both (a) and RUC_NESDIS.

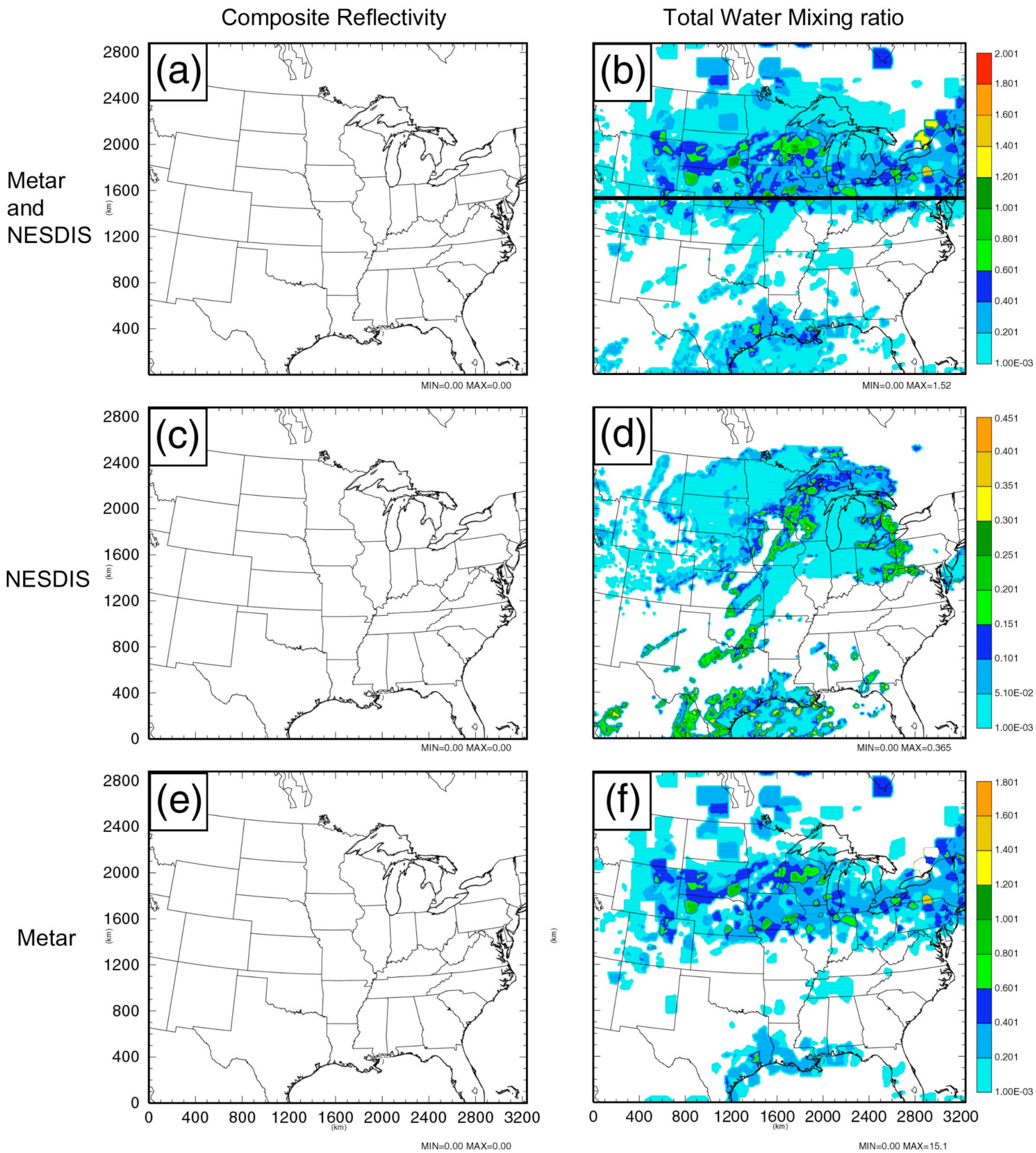

Fig. 5 Composite reflectivity (left column) and the vertical amount of total water mixing ratio (right column) from the experiments RUC_both (a and b), RUC_NESDIS (c and d), and RUC_METAR (e and f)

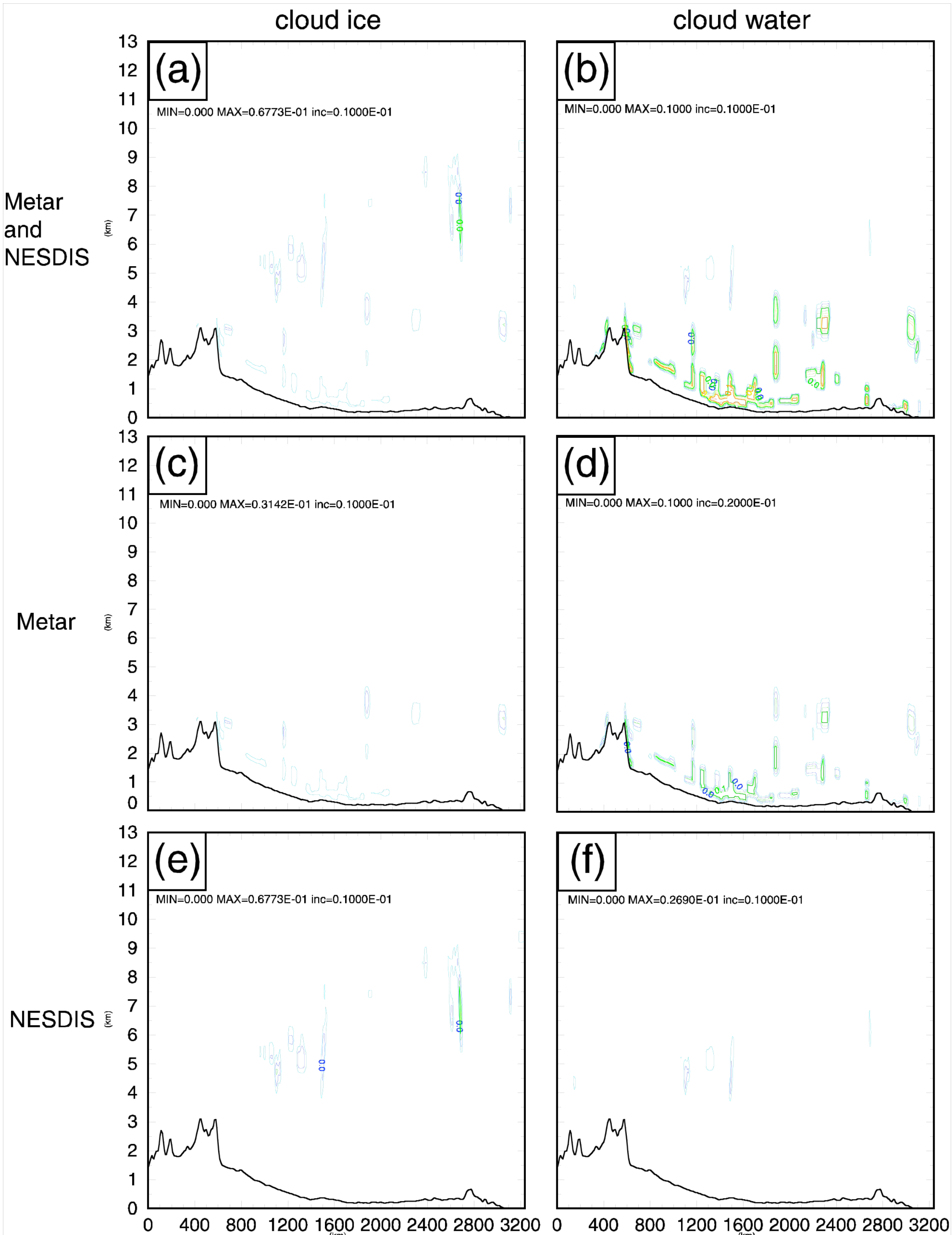

Fig. 6 X-Z cross-section of cloud ice (left column) and cloud water (right column) along the line shown in Fig. 5b from the experiments RUC_both (a and b), RUC_METAR (c and d), and RUC_NESDIS (e and f)

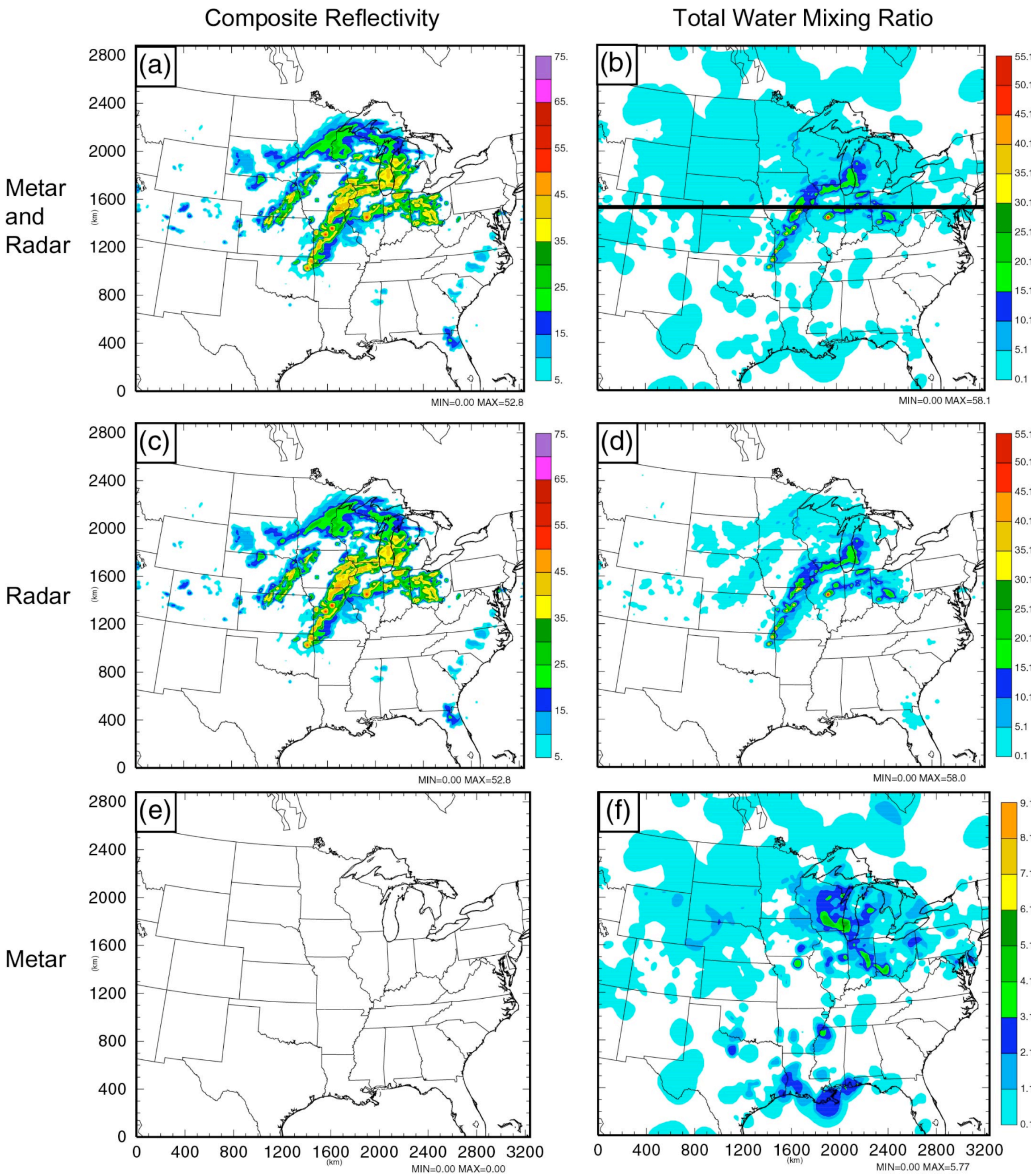

Fig. 7 Composite reflectivity (left column) and the vertical amount of total water mixing ratio (right column) from the experiments ARPS_both (a and b), ARPS_RADAR (c and d), and ARPS_METAR (e and f)

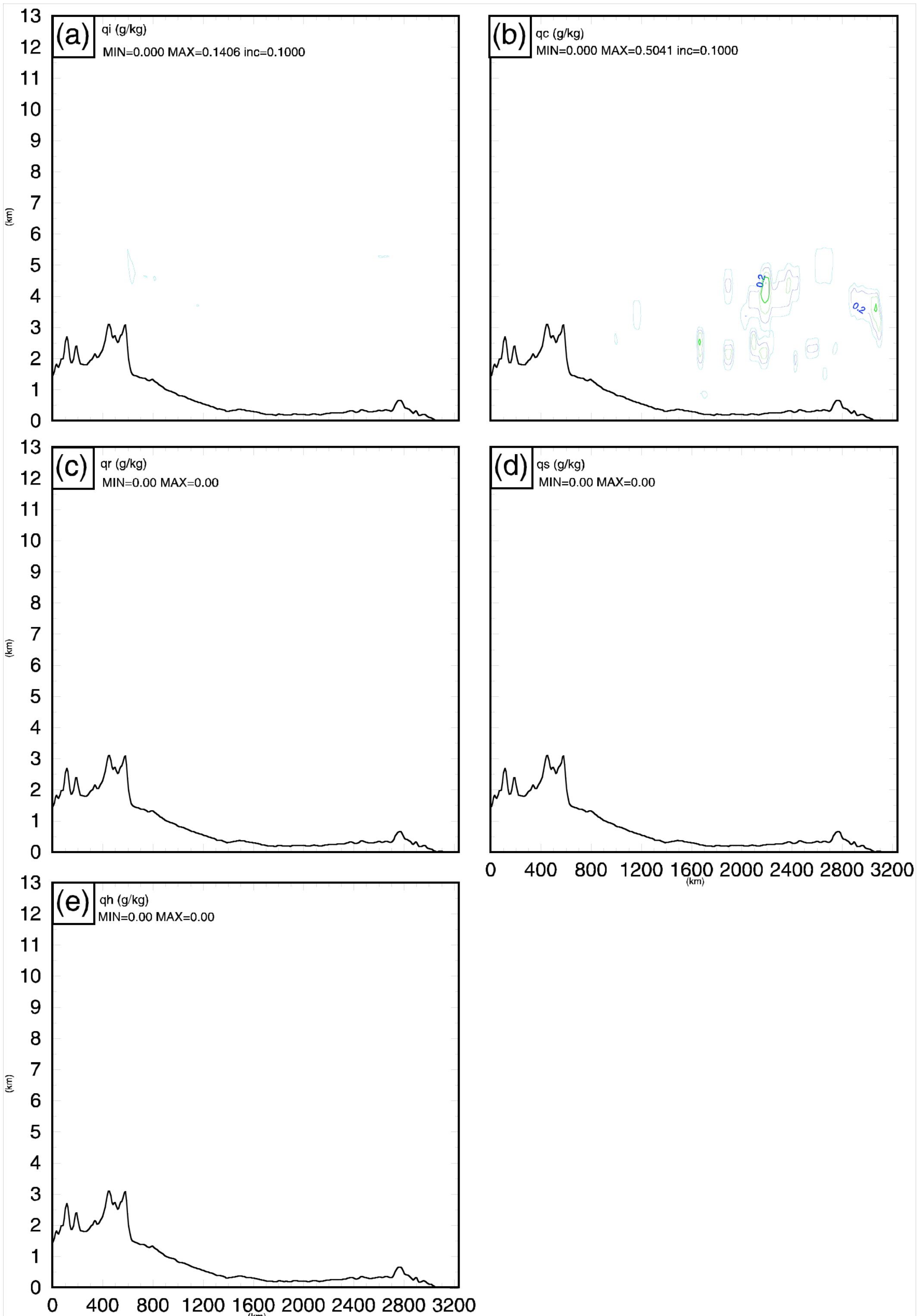

Fig. 8 X-Z cross-section of cloud ice (a), cloud water (b), snow (c), rain (d), hail (e), and reflectivity along the line shown in Fig. 7b from the experiments ARSP_METAR.

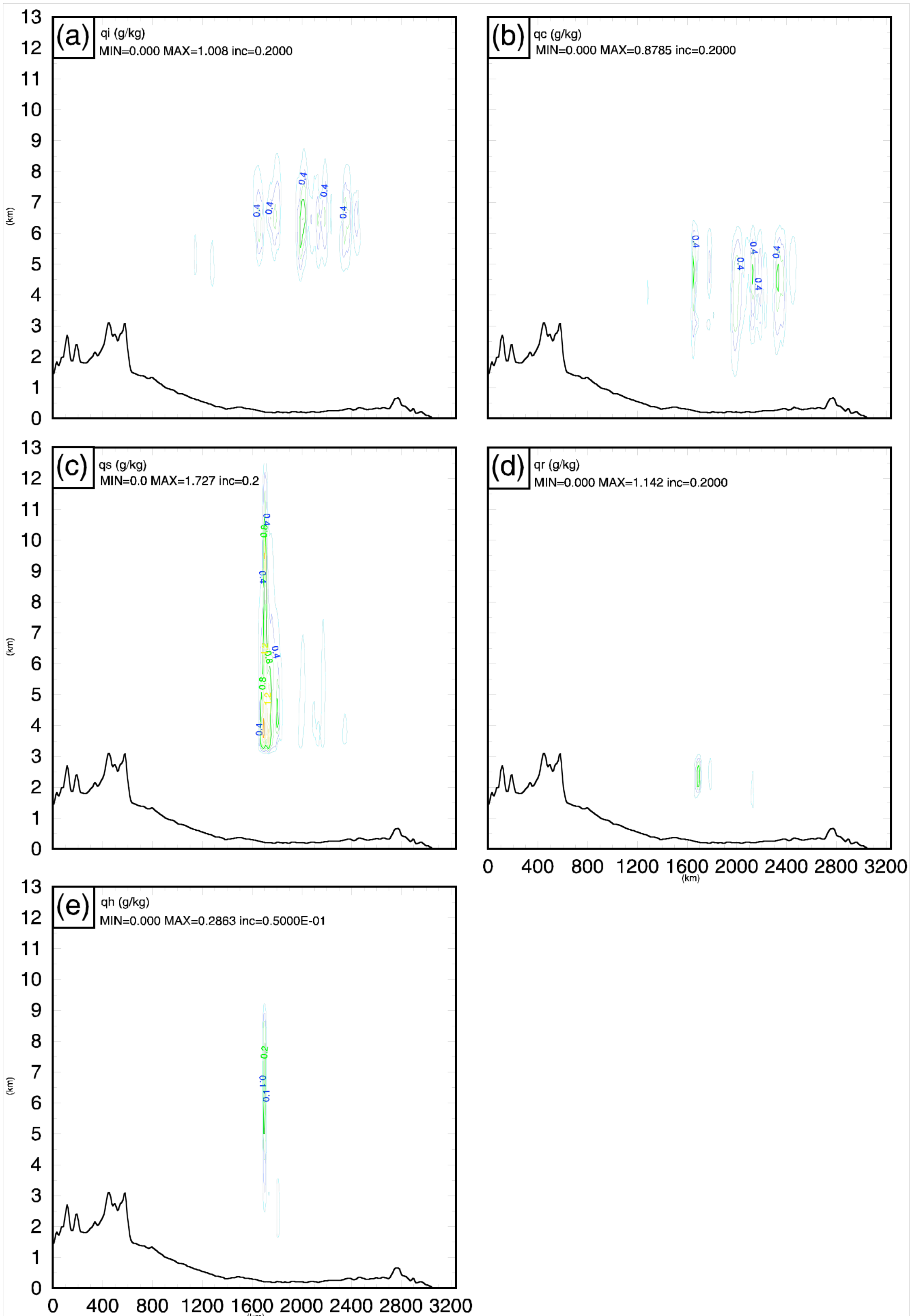

Fig. 9 Same as Fig. 8 but for the experiment ARPS_RADAR

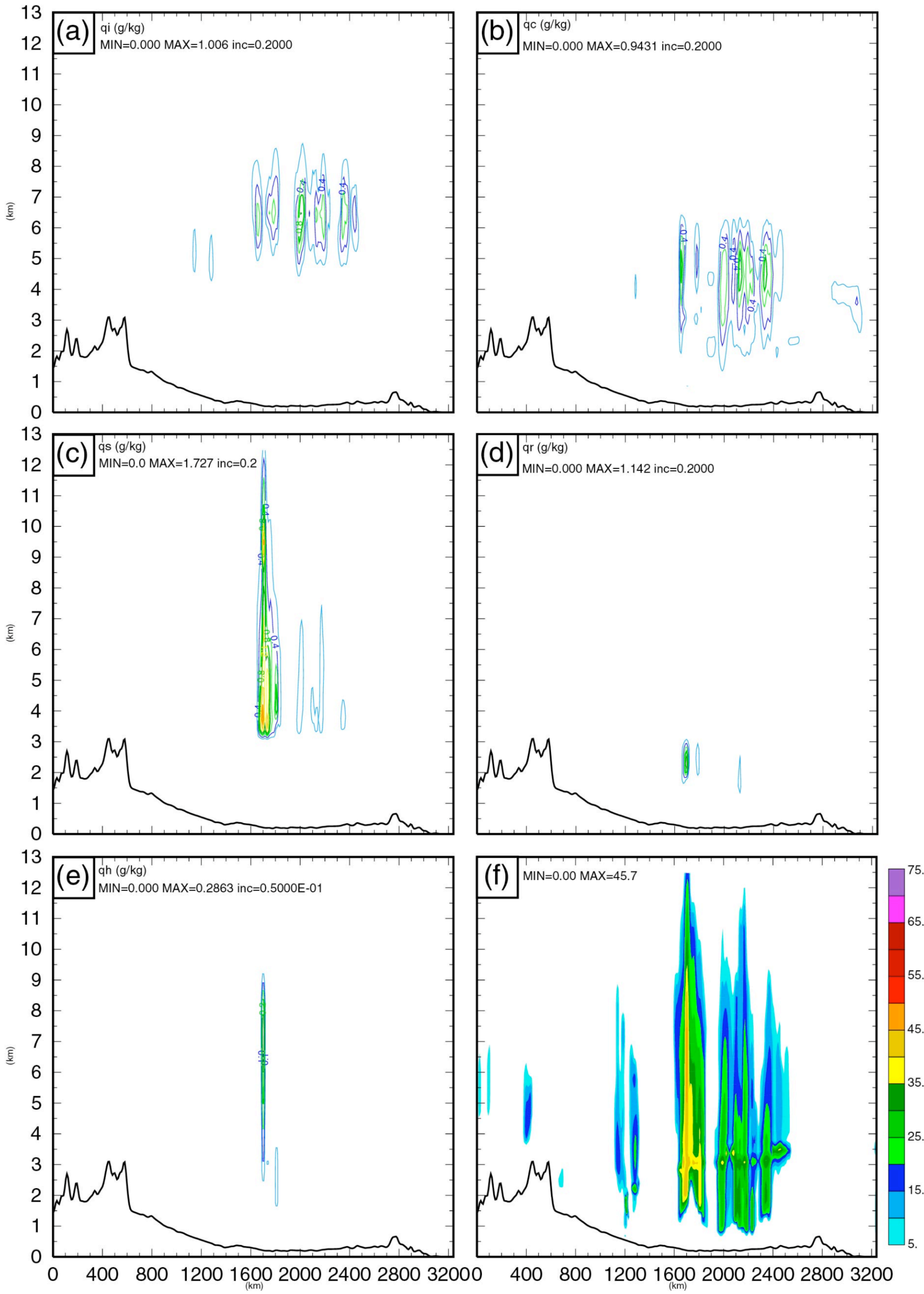

Fig. 10 Same to Fig. 8 but for the experiment ARPS_both

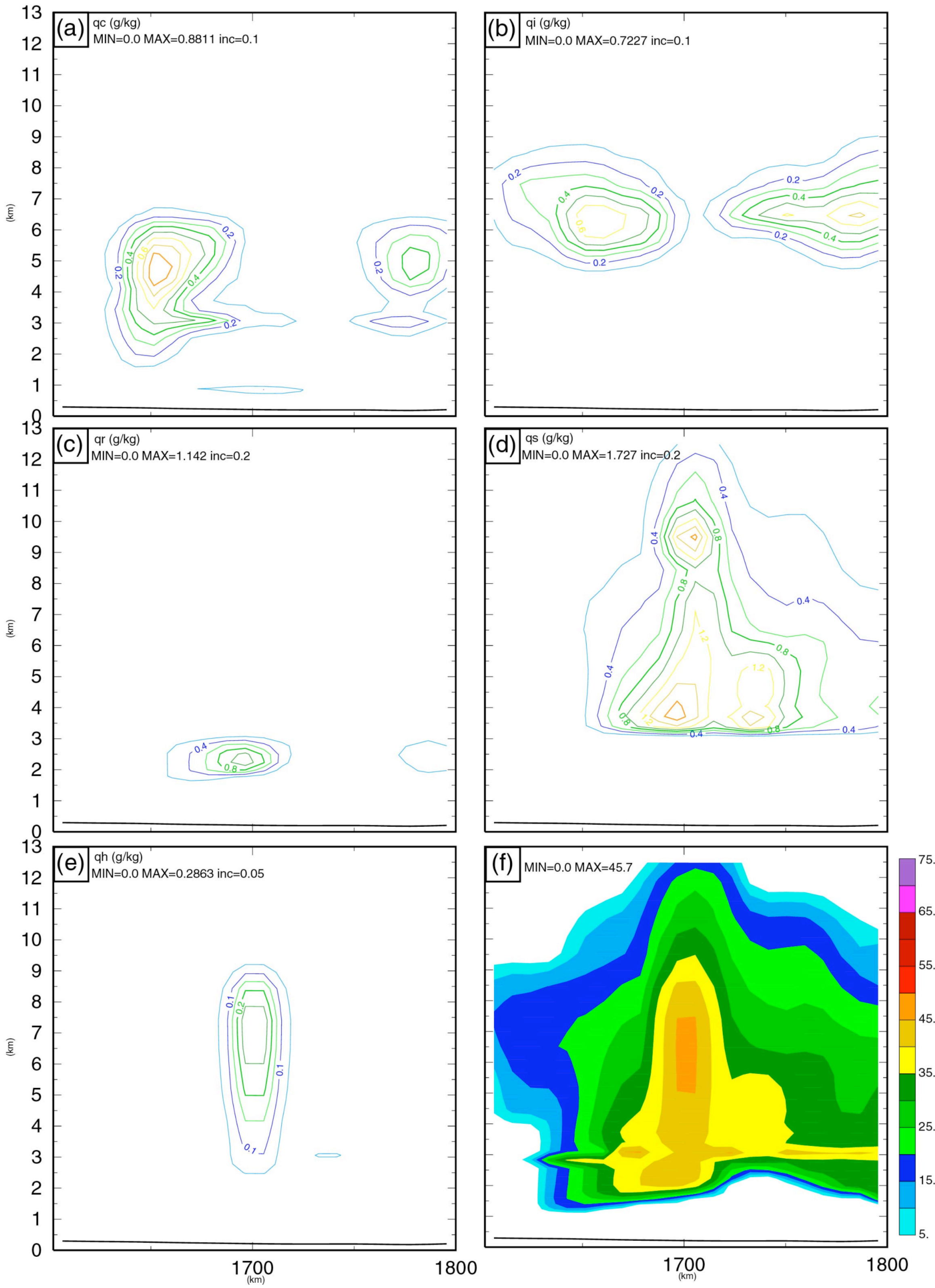

Fig. 11 X-Z cross section of cloud water (a) , cloud ice (b), rain (c), snow(d), hail (e), and reflectivity (f) long the line shown in Fig. 7b from the 03 UTC 13 analysis of the experiment ARPS_both. The range of X coordinate is between 1600 and 1800 km.

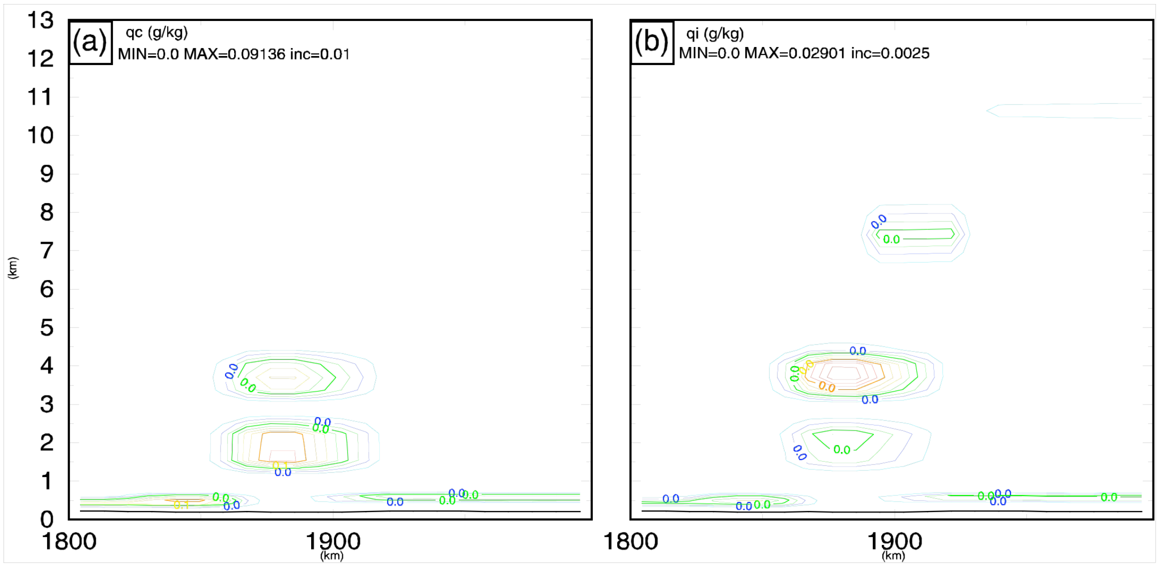

Fig. 12 X-Z cross section of cloud ice (right) and cloud water (left) long the line shown in Fig 5b from the 03 UTC analysis of the experiment RUC_both. The range of X coordinate is between 1800 and 2000 km.

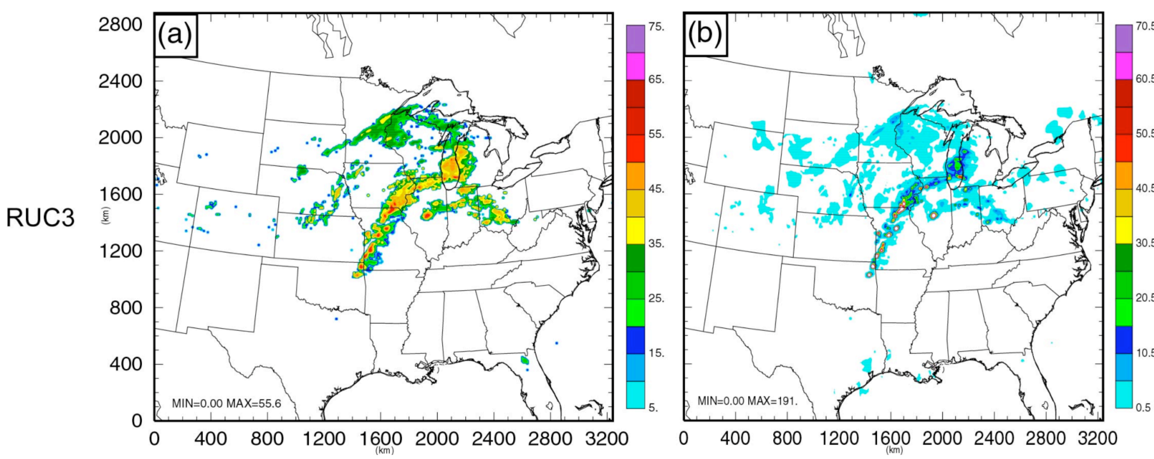

Fig. 13 Analyzed composite reflectivity (left) and the vertical amount of total water mixing ratio (right) from the experiment RUC3 at 03 UTC 13 2006

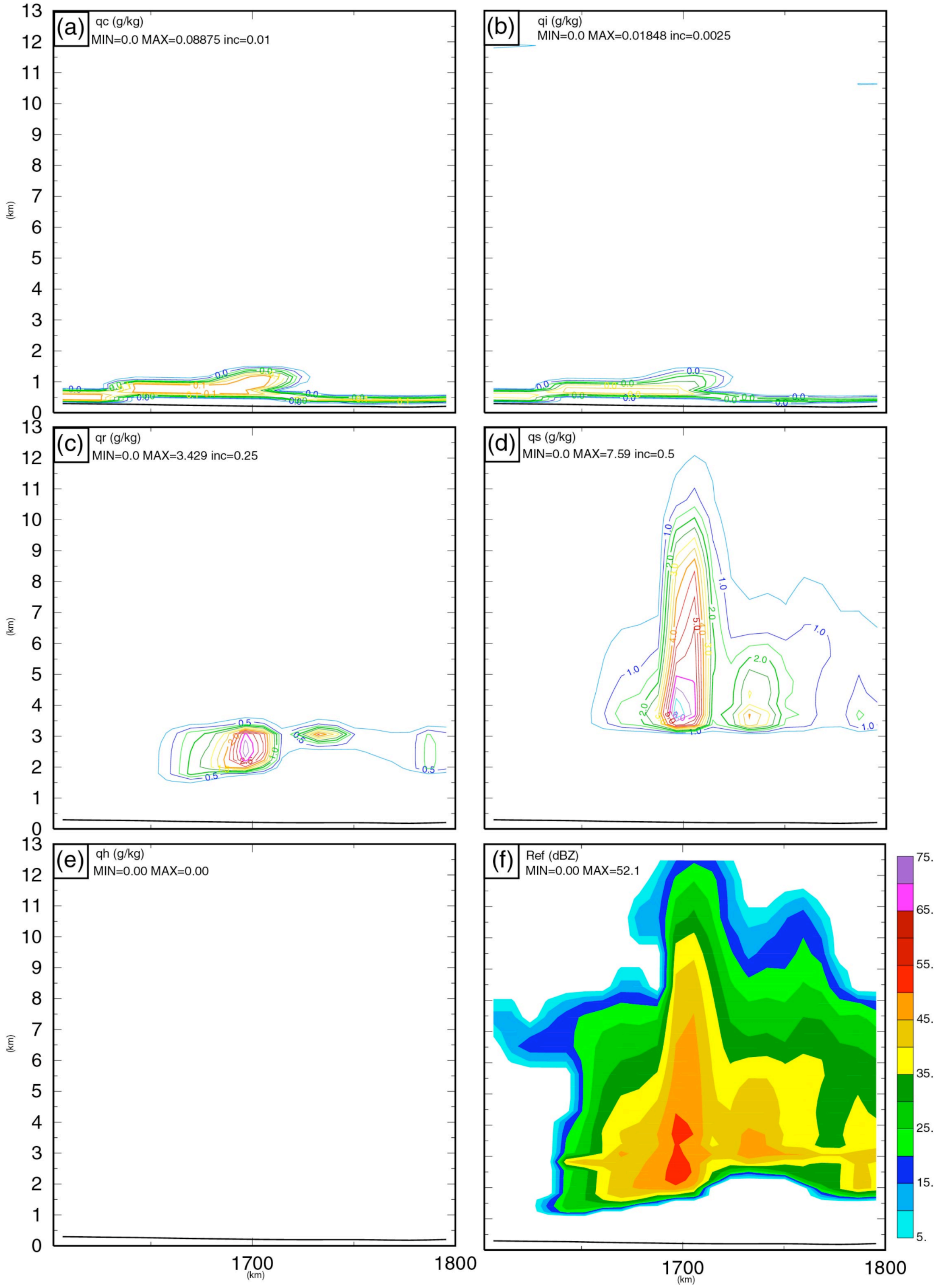

Fig. 14 X-Z cross section of cloud water (a) , cloud ice (b), rain (c), snow(d), hail (e), and reflectivity (f) long the line shown in Fig. 7b from the experiment RUC3. The range of X coordinate is between 1600 and 1800 km.

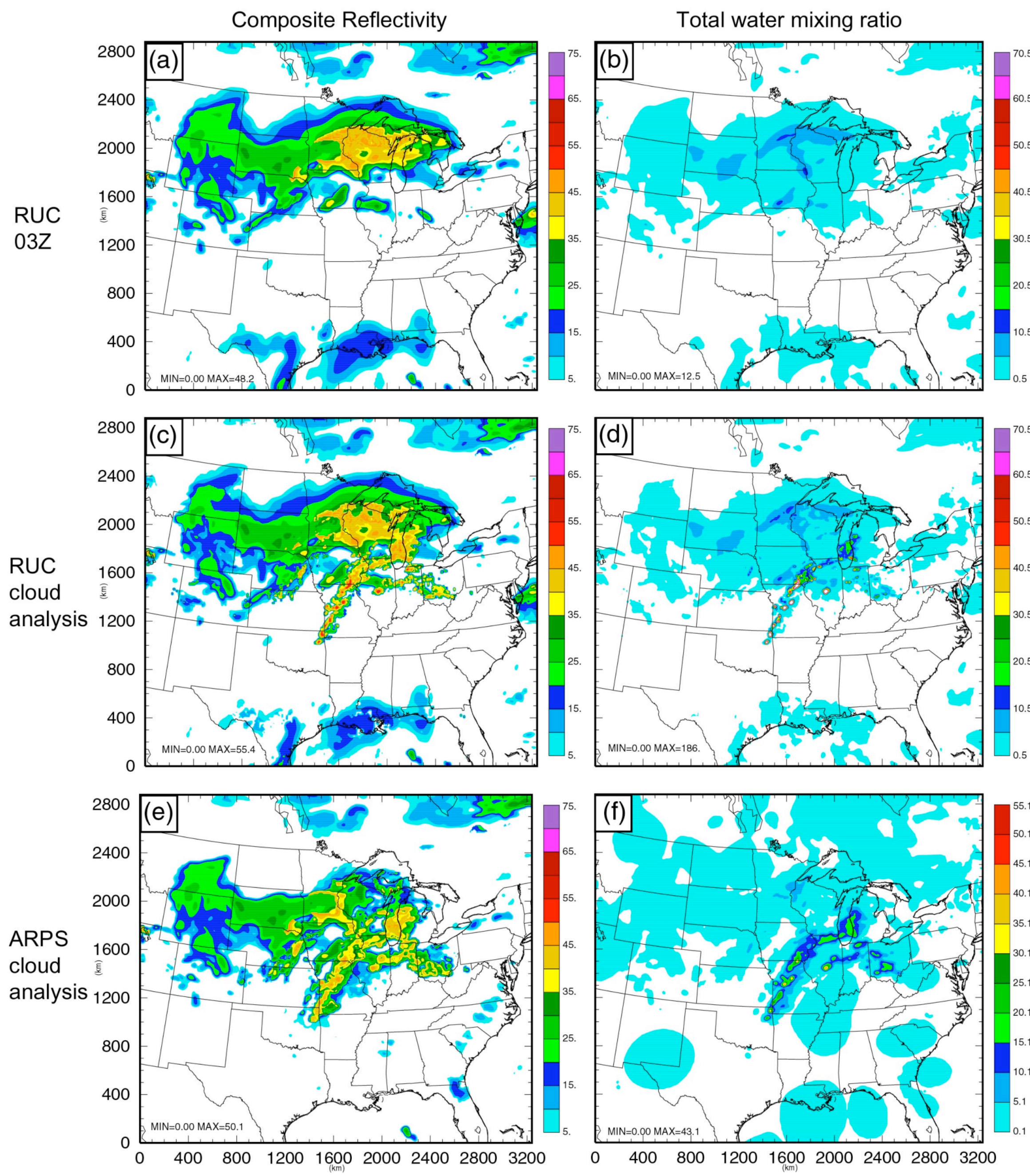

Fig. 15 Composite reflectivity (left) and the vertical amount of total water mixing ratio (right) from RUC 03Z background (upper) the experiment RUCbk3 at 03 UTC 13 2006(lower)

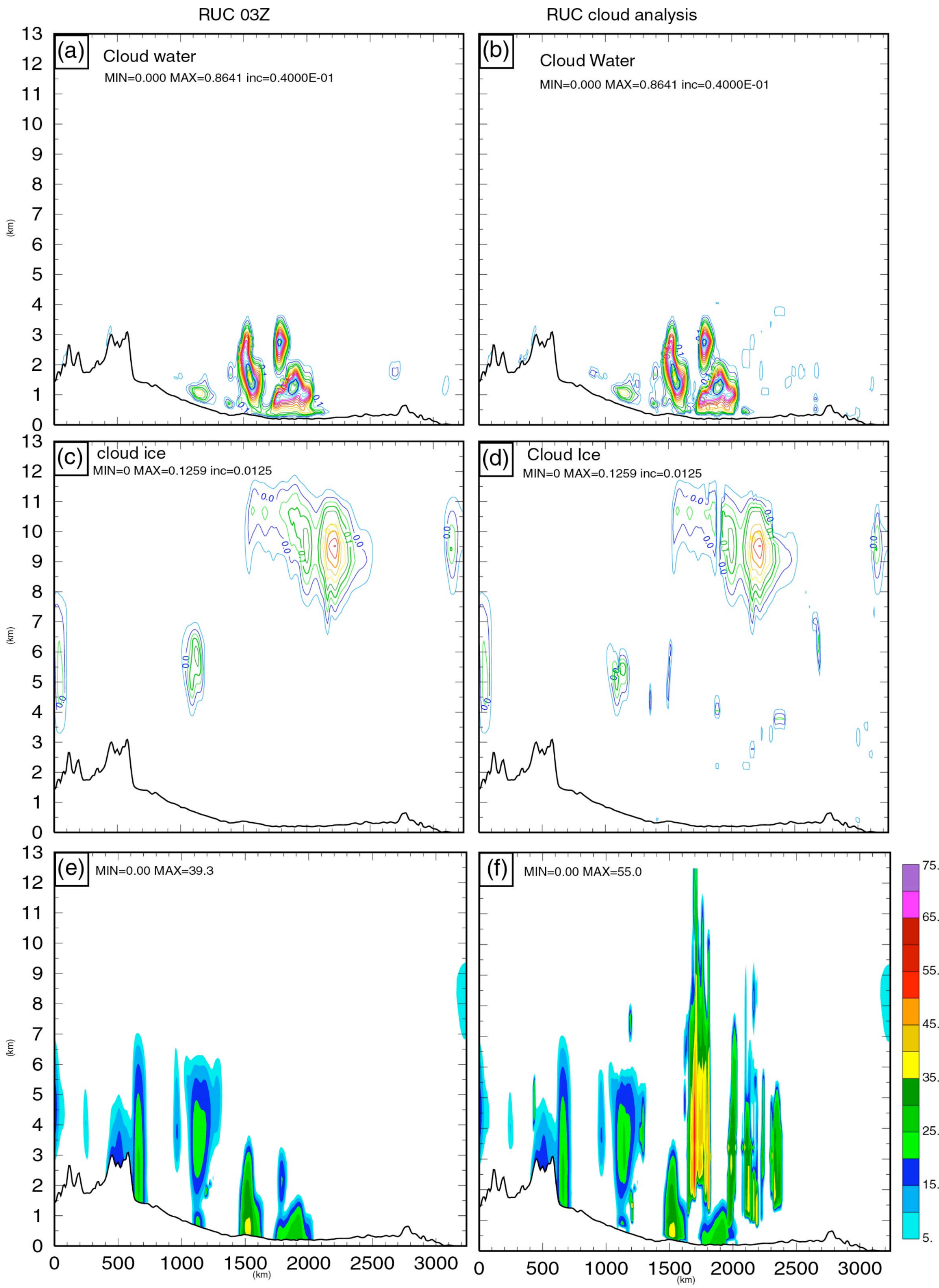

Fig. 16 X-Z cross section of cloud water, cloud ice, snow, rain, hail, and reflectivity long the line shown in Fig. 5b from the 03 UTC 13 analysis of the experiment RUC3_RUCbk and RUC 03Z background.

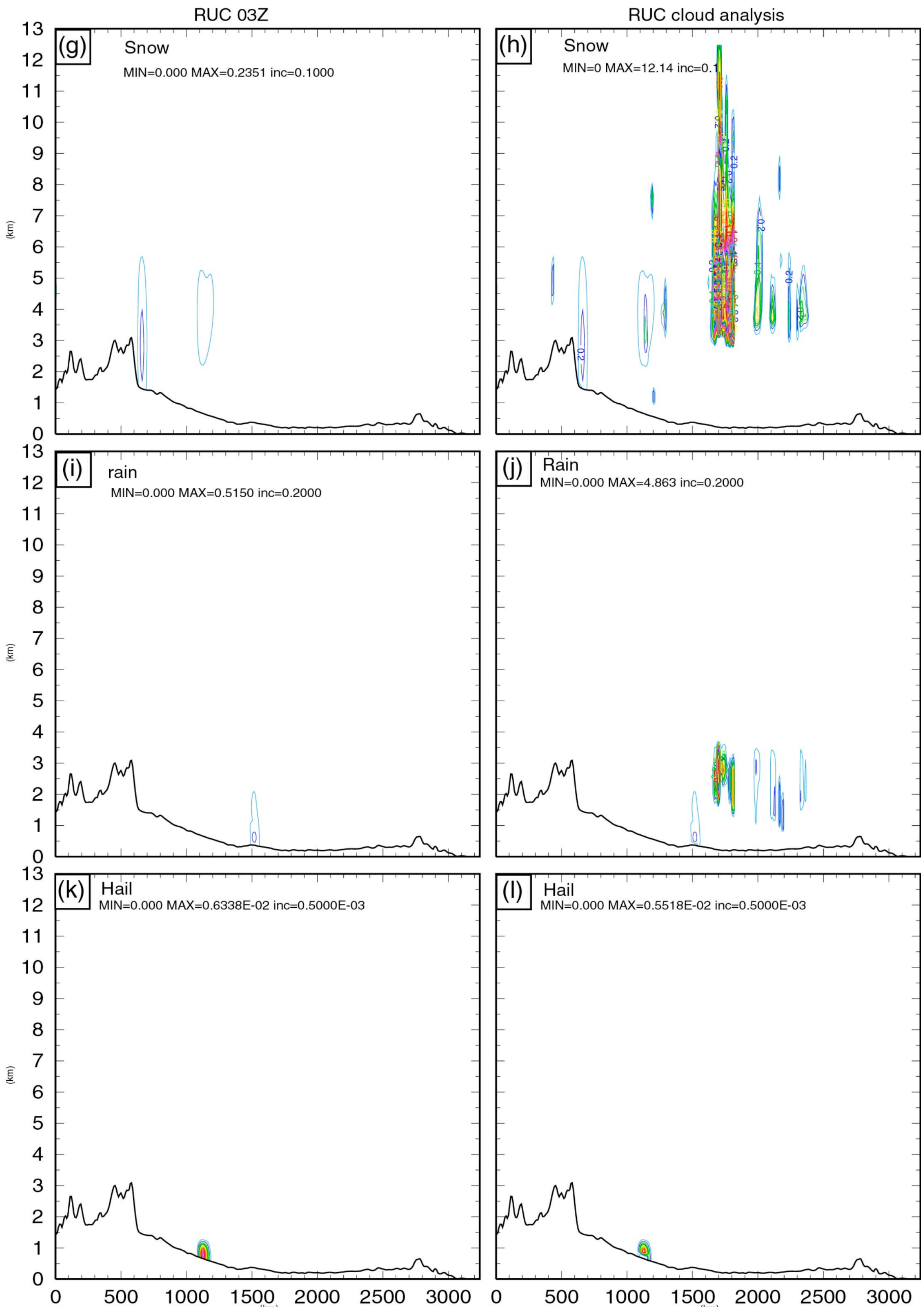

Fig. 16 Continued

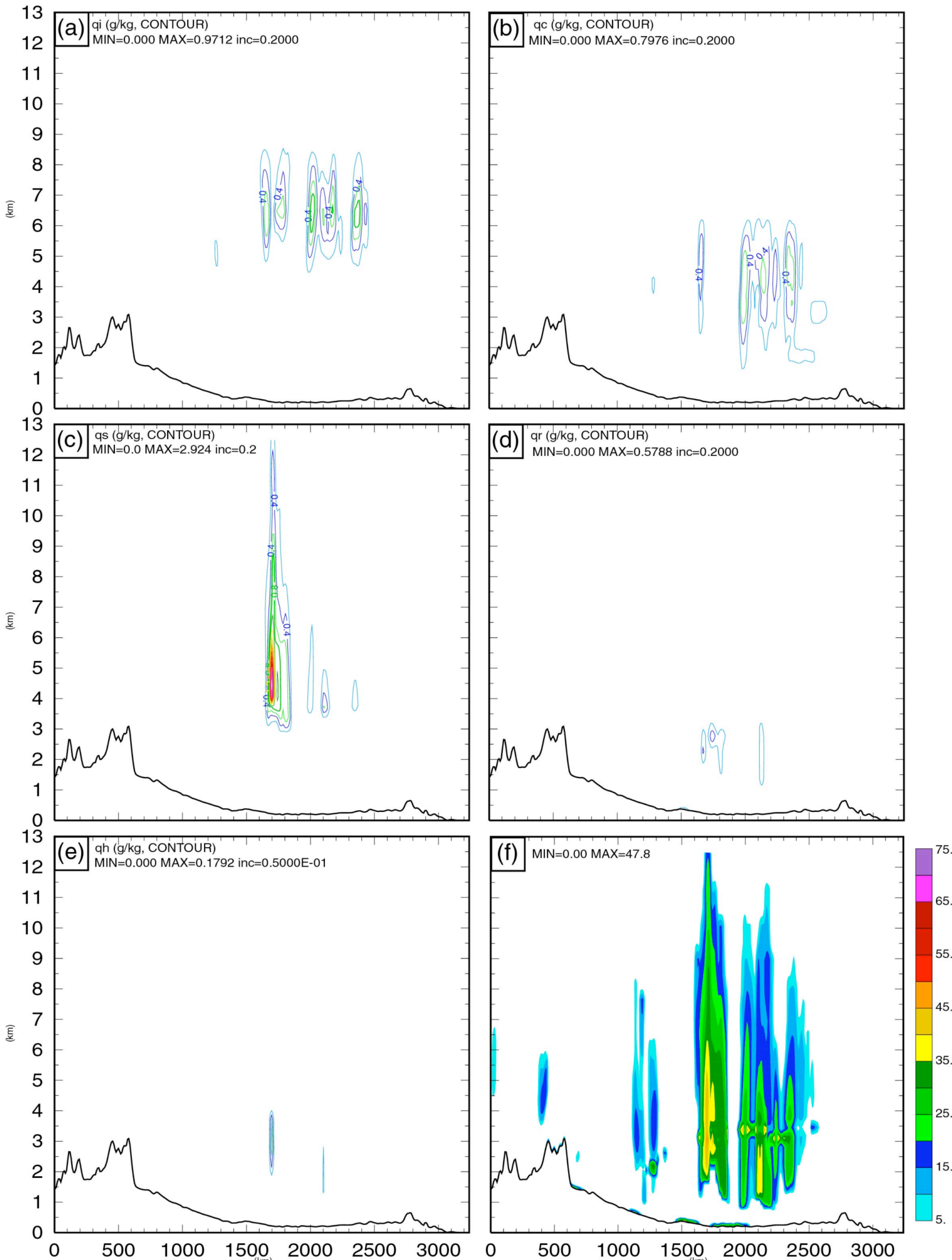

Fig. 17 X-Z cross section of hydrometeors and reflectivity long the line shown in Fig. 5b from the 03 UTC 13 analysis of the experiment ARPS2_RUCbk.

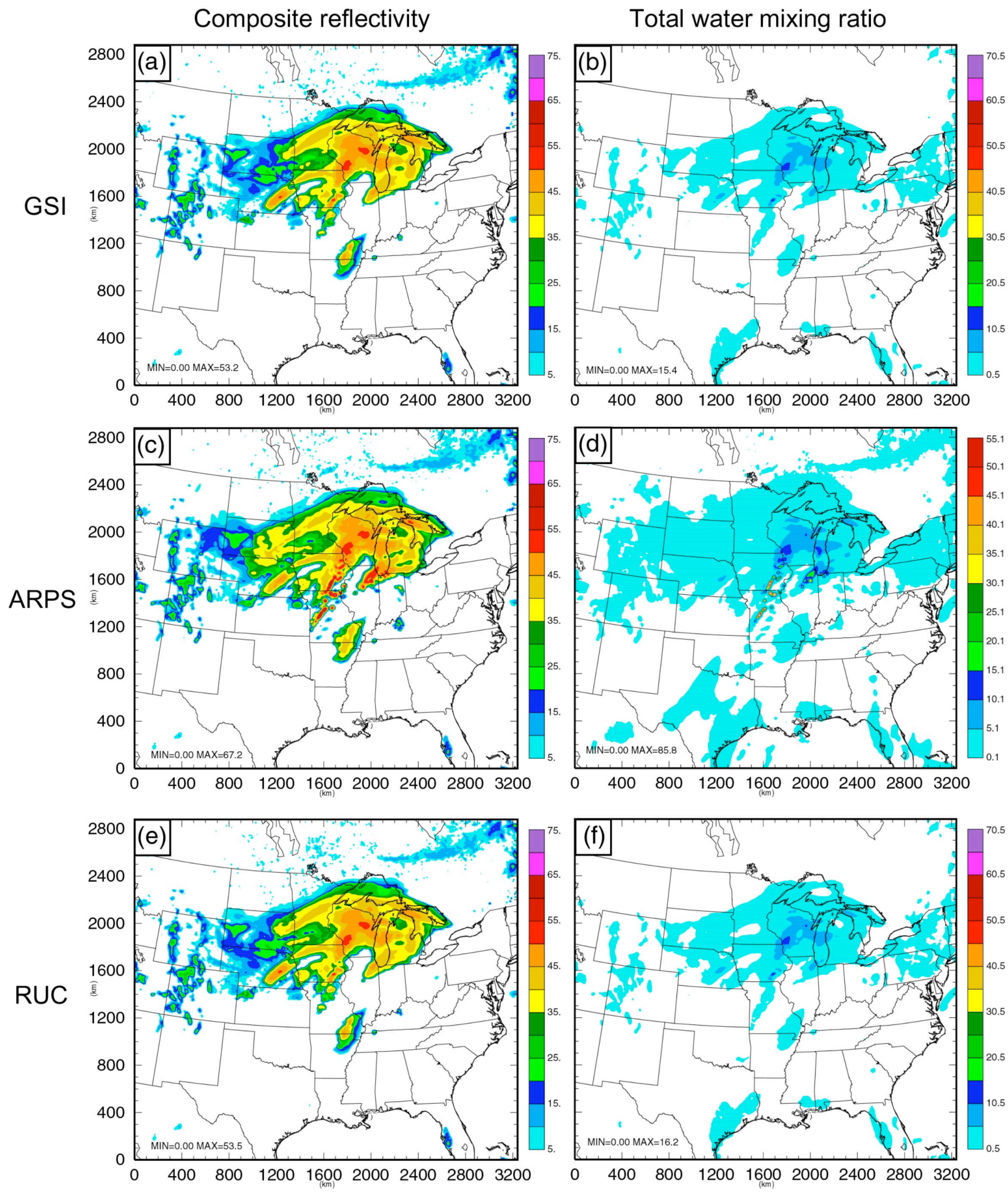

Fig. 18 Predicted composite reflectivity (left column) and vertical amount of total water mixing ratio (right column) valid at 04 UTC 13 2006 from the experiments GSI (a and b), ARPS_both (c and d), RUC_both (e and f), and RUC3 (g and h)

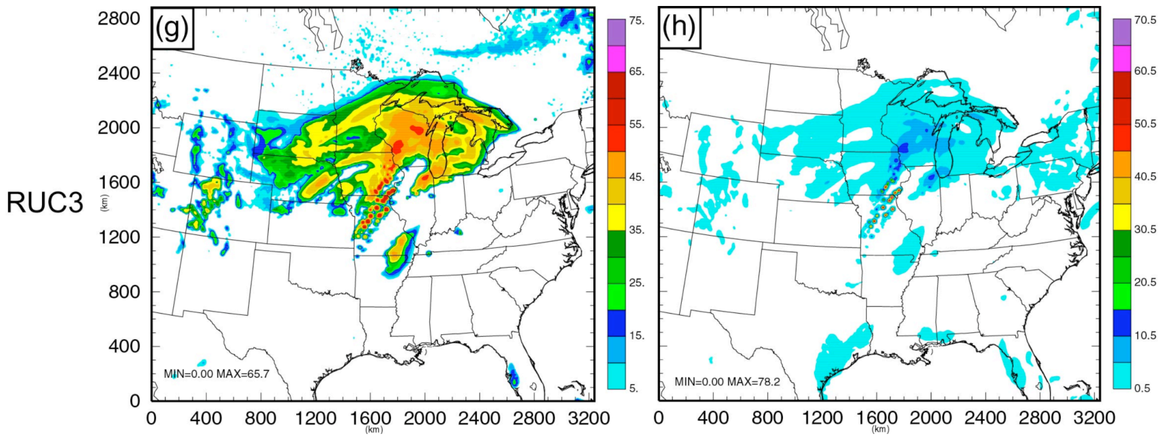

Fig. 18 Continued

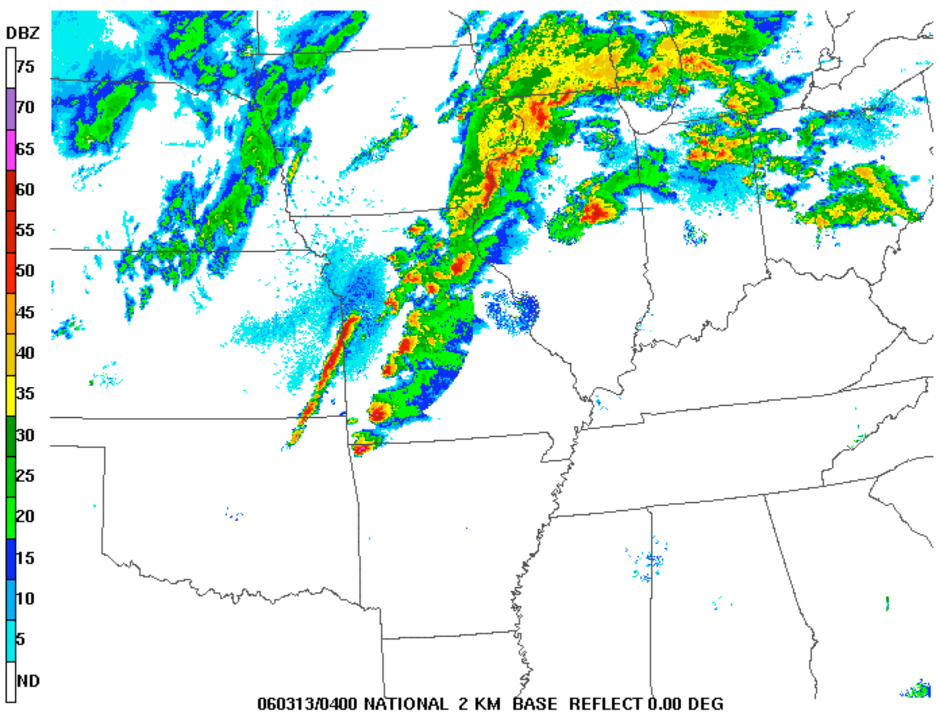

Fig. 19 Radar base reflectivity at 04 UTC 13 March 2006